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6753 East **47**st Avenue, Unit **D**
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In-X
Inspired Respiratory Care Products

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February **18,2002**

RSPA-02-11622-3

Associate Administrator for Hazardous Materials Safety
Research and Special Programs Admin.
U.S. Department of Transportation
400 **7**th Street, SW.
Washington, D.C. **20590-0001**
Attention: **DMH-31**
Ms. Cheryl West Freeman
General Engineer

02 FEB 19 AM 5:14

Ref: 12933-N Request for an Exemption under 49 CFR Subpart B

A-42541

Reply to attention of:

Ronald Rogowski
Vice President of Production
In-X Corporation
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Denver, CO **80216**
Phone # **(303) 574 3115** ext **105**
Fax # **(303) 574 3114**
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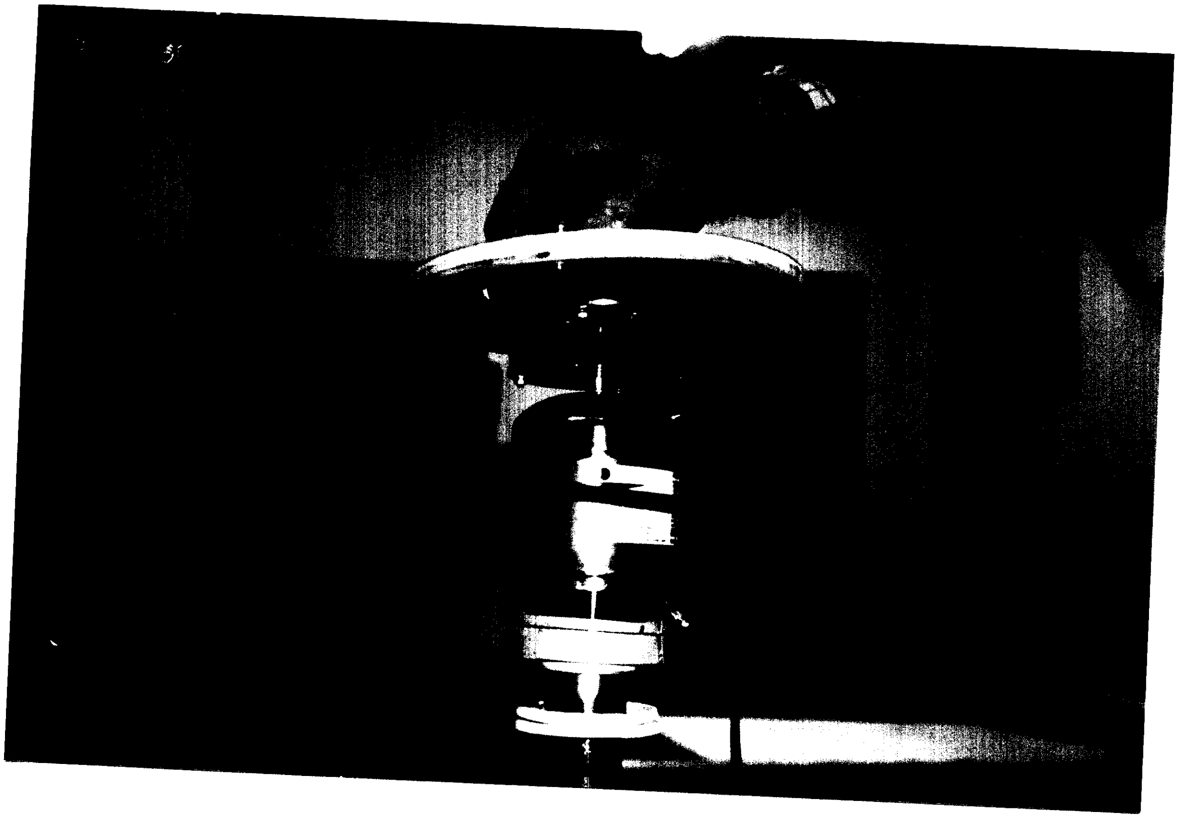
Dear Cheryl,

Enclosed are two sets of documents which I hope you will find useful. I have tried to supply documentation which explains what a Cryocooler is, and what it does. I tried not to burden you with an overabundance of "paper", because this stuff gets fairly technical very quickly. However, I will gladly go into greater detail if you and your group so request.

Respectfully,

Ronald Rogowski

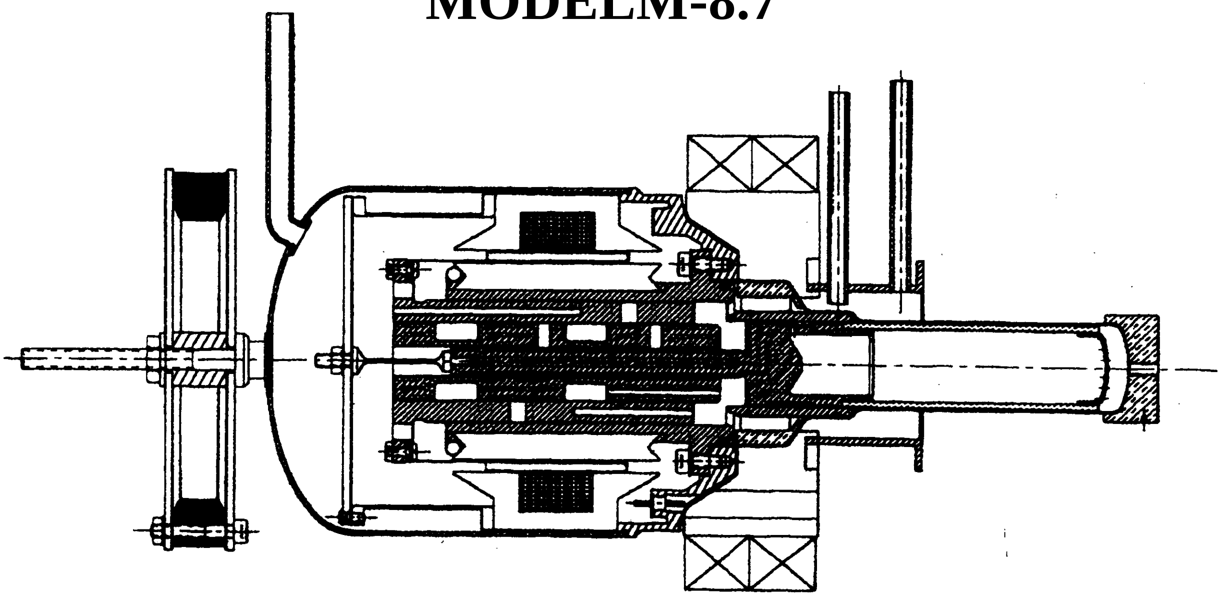
Ronald Rogowski
Vice President



SUNPOWER INC.

New High Efficiency Small Cryocooler

MODELM-8.7



Advantages

- Compact size and lightweight
- Exceptional COP for small cooling capacities at temperatures below 150K
- Electronic controller available to maintain cold end temperature (<15 W additional input required)
- Hermetically sealed
- No CFCs, HCFCs, HFCs or oil
- Minimal vibration

Principle of Operation

The machines implement the Stirling refrigeration cycle. A confined volume of helium gas is shuttled back and forth between the cold and warm ends of the machine. The gas is expanded in the cold end to absorb heat from the thermal load, and compressed at the warm end to reject heat to the environment.

Reliability

The machines are routinely sealed to a leakage rate of better than 1×10^{-9} standard cubic centimenters per second. Linearly reciprocating internal components levitate on gas bearings, virtually eliminating friction and wear. Previous machines demonstrate no primary bearing failures during extended runs and stress testing. Confidence in overall reliability is increasing rapidly with additional operating time.

Specifications subject to change without notice, as Sunpower continually improves the design.

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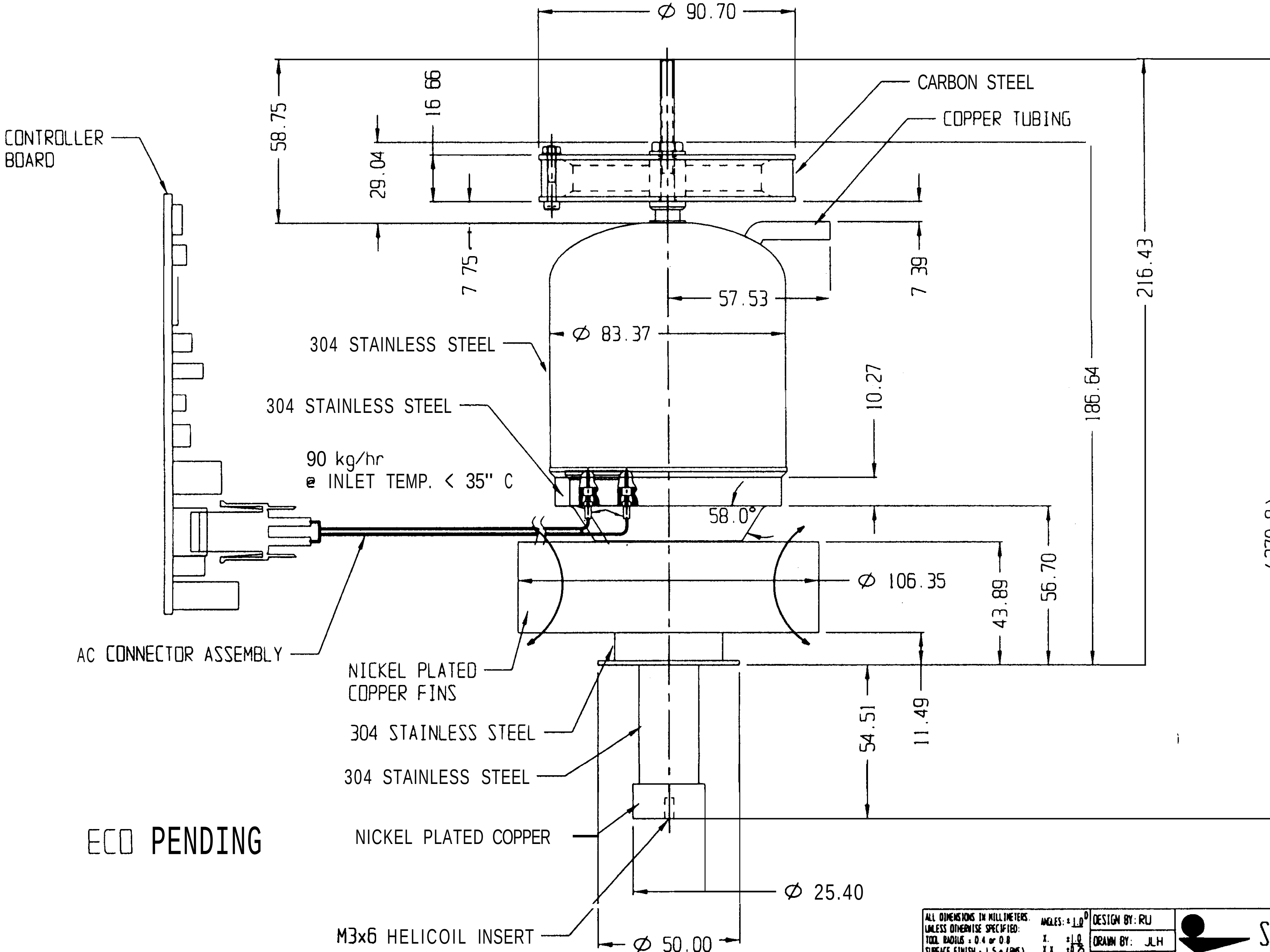

ECO PENDING

ANSI Y14.5M - 1982

ALL DIMENSIONS IN MILLIMETERS. UNLESS OTHERWISE SPECIFIED: TOOL RADIUS : 0.4 or 0.8 SURFACE FINISH : 1.5μm (RMS) OR BETTER DEBURR ALL EDGES	ANGLES: ± 1.0° X. ±1.0 X.X ±0.25 X.XX ±0.10	DESIGN BY: RU DRAWN BY: JLH SIZE: C SCALE: 1:1 QTY/UNIT 1	SUNPOWER, INC. Athens, Ohio
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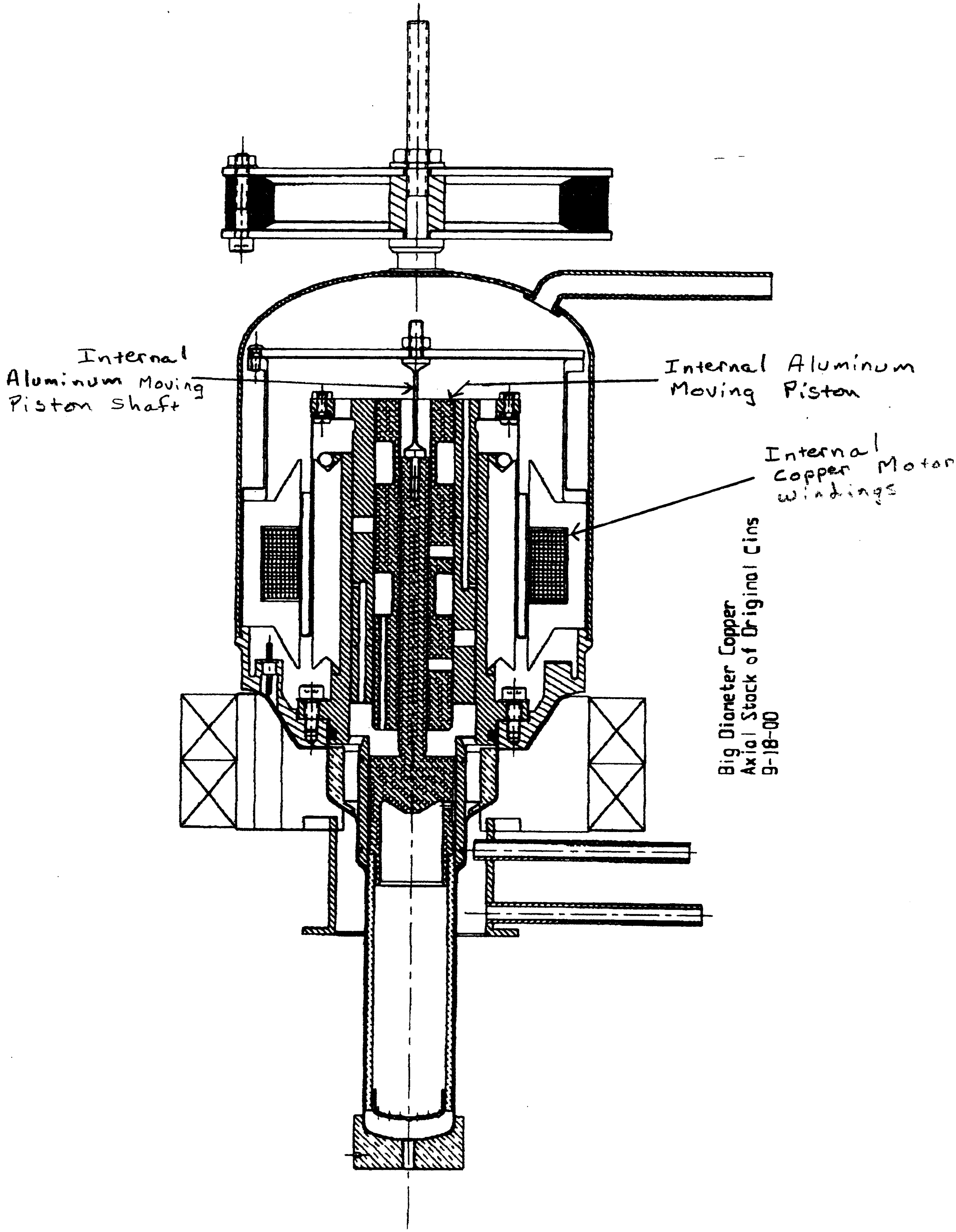
DOCUMENT NUMBER 012201-SS-01-01		TITLE M87 CONTROL DRAWING	

CRYOCOOLER

MODEL M-87



SUNPOWER Inc Paper on Cryocoolers.

MINIATURE STIRLING COOLERS

by

D.M.Berchowitz
Chief Engineer
Sunpower, Inc
Athens, Ohio

ABSTRACT

Free-piston Stirling cycle coolers appear to offer the best opportunities for compact cooling where high specific capacities (lift/mass) are required. Furthermore, they are quiet, efficient, have low vibration and recent developments suggest that very long life may be expected. These characteristics are vital when considering active cooling (refrigeration) for electronic components. Comparisons are made to Rankine (vapor compression) and thermoelectric cooling. Free-piston Stirlings have only recently been seriously considered for electronic cooling and studies suggest that much is possible in terms of miniaturization. However, there are fundamental limits imposed by thermodynamics that restrict miniaturization no matter how close the cooling machine comes *to* operating without losses,

INTRODUCTION

As miniaturization of electronics continues, the problems of heat removal become more difficult. In addition, many electronic systems perform better (or only) at subambient or cryogenic temperatures. For all these applications, the basic performance requirements include lift (heat transferred at cold end, also referred to as *capacity)*, temperature of the cold end, and input power. As temperatures *go* lower, input increases for the same lift. This is a consequence of the laws of thermodynamics and is true irrespective of the means to achieve cooling. However, there is a minimum power level for a given cold temperature and lift. This minimum power is dictated by the Carnot efficiency, which cannot be exceeded. For coolers and refrigerators the efficiency is generally represented in terms of the coefficient of performance (COP) as a fraction of the maximum possible COP (the Carnot COP).

$$\mathrm{COP} = \frac{\text{Heat lift [W]}}{\text{Power input [W]}} \qquad (1)$$

Thus the fraction of ideal performance would be given by:

$$\eta = \frac{\mathrm{COP}}{\mathrm{COP}_{\mathrm{Carnot}}} \qquad (2)$$

where the $\mathrm{COP}_{\mathrm{Carnot}}$ is a function only of the absolute temperatures of the source and sink, namely:

Conference presentation: NEPCON East '93, National Electronics Packaging and Production Conference, Boston, MA. June *14-17,* 1993.

$$COP_{Carnot} = \frac{T_c}{T_h - T_c} \qquad (3)$$

where T_c is the absolute cold temperature and T_h the &solute warm temperature.

Thus if the lift per unit of input is known for given source and sink temperatures, then the fraction of ideal performance may be determined by which measure the efficiency of different systems may be compared.

Other important factors for comparing different systems is the specific lift (lift per unit mass) and the lift per unit volume. These factors give an idea of *cost* and *size* [1].

FREE-PISTON STIRLING CYCLE

The Stirling cycle alternately compresses a fixed mass of *gas* (usually helium) at one temperature level and expands it at another in a closed regenerative cycle in order to either lift heat or do work. The thermodynamic cycle is covered in more detail elsewhere [1, 2]. Suffice it to say here that in its ideal form, the Stiriing cycle has the highest possible efficiency for any thermodynamic cycle.

Originally Stirling machines were all driven kinematically, that is, by way of crank shafts and connecting rods as is used in most positive displacement machinery. The kinematic configurations have lead to a number of problems peculiar to the Stiriing, these being the contamination of the internal heat exchangers by the lubricating oil, the difficulty in containment of the pressurized working *gas* and high friction in the seals due to the more severe duty required of them. The sum effect being to bar these machines from becoming long life, low cost products. In an effort to circumvent these problems, W. T. Beale suggested the free-piston configuration which is shown in Figure 1 [3]. The bee-piston Stirling employs the internal gas pressures and a linear motor to move the reciprocating components in the proper fashion. In so doing, a number of benefits accrue, namely:

i) The side loads on the moving parts *are* so low that it becomes practical to utilize gas bearings and therefore avoid *the* need for lubricating oil. Since gas bearings operate without contact, there is practically no wear or friction and long life *can* be expected in addition to high mechanical efficiency.
ii) A linear motor for supplying power to the piston is easily placed within the pressure vessel making it possible to hermetically seal the unit which avoids the working *gas* leakage problem.
iii) Modulating the machine becomes a simple matter of adjusting the piston stroke which for a linear motor simply means controlling the input voltage.
iv) The motion of the moving parts are almost pure sinusoids. Thus, the higher harmonic content in the vibration of the unit is very small. This makes it *easy* to balance the machine with a simple dynamic absorber to levels of very low residual amplitude. A machine balanced in this manner is extremely quiet.
v) Simplicity of construction. The basic machine has only two moving parts and no valves.

MINIATURE STIRLING COOLERS
by D.M.Berchowitz

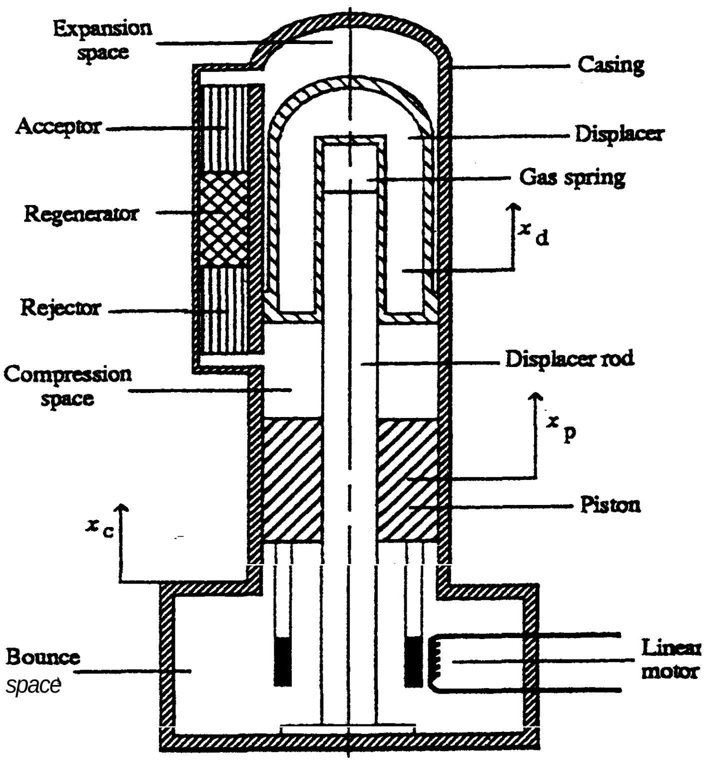


Figure 1 – General arrangement of a be-piston Stirling cooler driven by a linear motor

Mechanically, therefore, the free-piston / linear motor Stirling cooler is of high overall efficiency and is able to *operate* reliably for extended periods of time. Its behavior may be understood by describing it as a tuned mechanical oscillator where the resonances of the displacer and piston are such so as to obtain an optimum phase angle between their motions. A full theoretical treatment along these lines is available *in* [4].

COMPARISON WITH THERMOELECTRIC COOLING

The attraction of thermoelectric cooling is that there are no moving parts associated with the cooling process. Unfortunately efficiencies are very poor resulting in large units drawing high powers for moderate amounts of lift. Since the heat rejected is equal to the input power plus the lift, the rejector heat exchanger often needs to be fairly large. Figure 2 shows the performance of commercially available staged thermoelectric coolers compared to two free-piston Stiriing units. At temperatures of around -50°C (a delta T of between 80° to 100°C), the Stirling is over one *order* of magnitude better in COP than the staged thermoelectric. Thus, a lift of 40W at -50°C to +50°C ambient requires 2kW input for the thermoelectric device while only requiring 67W far the free-piston Stiriing cooler. This advantage increases dramatically as lower temperatures are approached (larger delta temperature).

MINIATURE STIRLING COOLERS

by D.M.Berchowitz

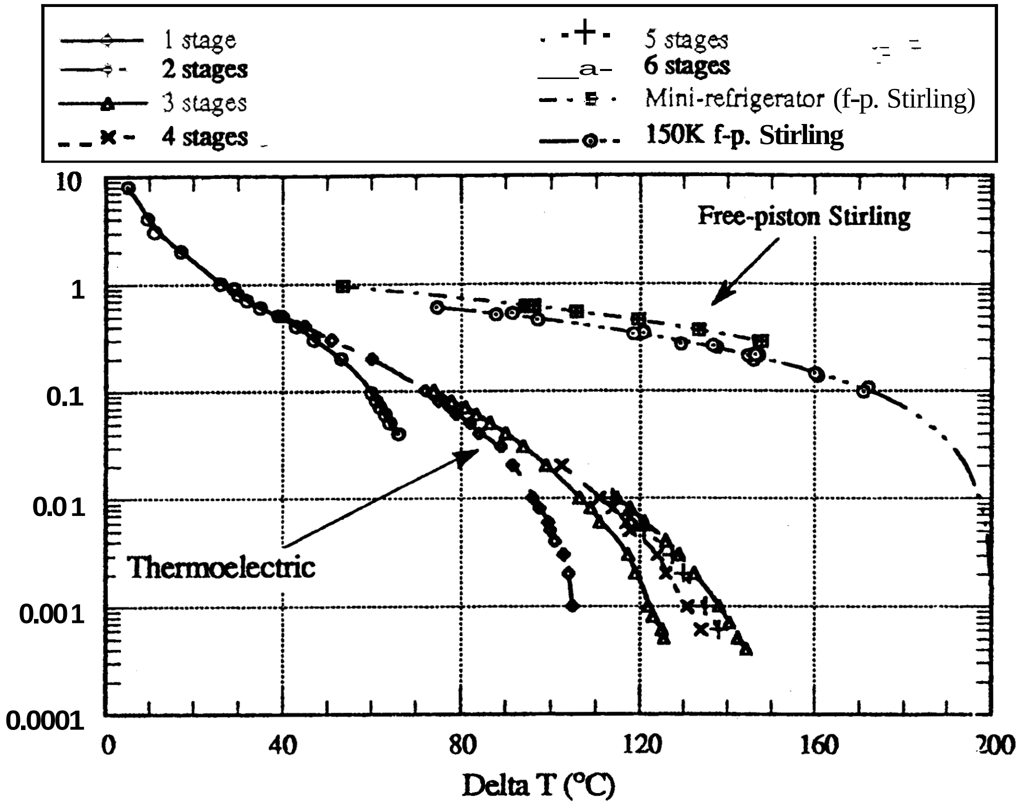


Figure 2 - Thermoelectric vs Free-Piston Stirling (Delta T = Reject temperature - Cold temperature)

8

COMPARISON WITH RANKINE COOLING

The Rankine (vapor compression) cycle is probably the most common means for providing cooling and is used almost exclusively for domestic refrigeration and air conditioning. This cycle tends to perform best in applications where the cold end temperature is above -30°C. For temperatures below -30°C the efficiency falls off and eventually it is necessary to cascade the cycle in order to obtain reasonable performance or even low enough temperatures. Cascading refers to the practice of using one cycle to precool the next one and so on until the desired temperature/lift combination is reached. Figure 3 compares the performance of the Rankine cycle and the free-piston Stirling in temperature ranges of several commercial applications. The curves labeled maximum Stiriing are considered to be the optimum performance with known science. The term AT refers to the temperature differential necessary to transfer heat in the heat exchangers. For the sake of simplicity both the acceptor (cold) and rejector (warm) heat exchangers are assumed to have similar ΔT's. For warmer temperatures (higher ideal COP's) it can be seen that except for the case of extremely small ΔT's, the Stirling has great difficulty competing against existing Rankine units. When large heat fluxes are involved, the ΔT's tend to be higher thus compromising the Stirling further. However, scale has an important effect here. Smaller capacity machines tend to have lower heat fluxes owing to the area to volume ratio which increases as the size decreases. For example, a small SOW lift free-piston Stirling was compared to a similar capacity Rankine unit at domestic refrigeration temperatures (about -30°C). The efficiency of the Stirling was measured to be 15% better than the Rankine as tested in the original refrigerator cabinet. If the power to the Stirling's cooling fan, which was particularly inefficient, is neglected, then the advantage increases to 50% [5]. Furthermore, the Stirling requires no heat rejection coil and is much smaller, lighter and operates more quietly. The free-piston Stirling thus competes with the Rankine as cold temperatures fall below about -30°C and as capacity goes down. Lower capacity tends to push the point of equivalent performance to warmer cold-end temperatures. A final point regarding the Rankine is the concern raised by the use of CFC refrigerants which have been implicated in the destruction of the earth's ozone layer. At warmer temperatures it now appears that safe refrigerants will be available. At lower temperatures, though, say below -40°C, no reliable environmentally acceptable alternatives have as yet been identified. The helium working gas of the Stirling is, of course, completely benign.

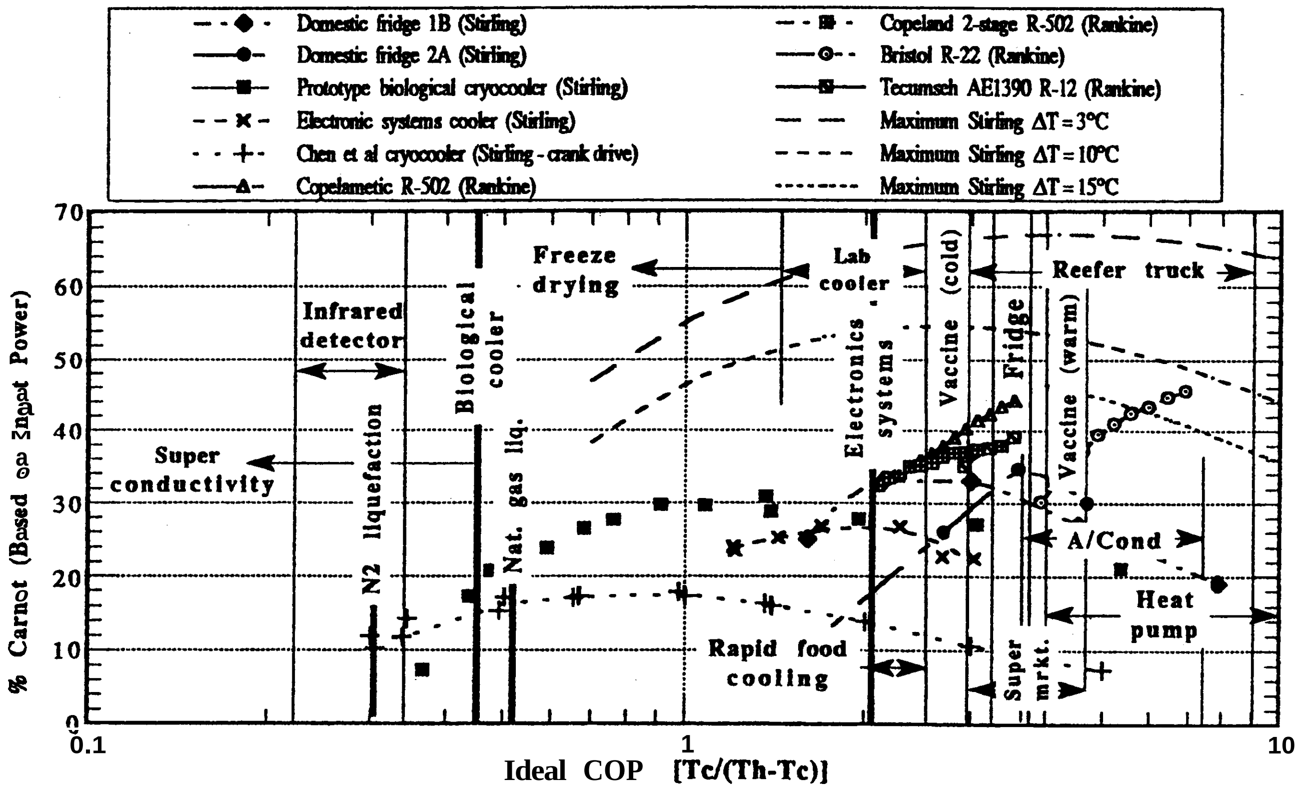


Figure 3 - General comparison of Stirling and Rankine for different applications [6]

Figure 4 shows a horizontally opposed free-piston Stirling cooler designed for use aboard the Space Shuttle where it will replace the original Rankine equipment. The horizontally opposed configuration achieves almost perfect balance without the need of a vibration absorber. The machine therefore operates with extremely low noise levels. Figure 5 shows the anticipated performance map for the unit. Modulation for the Stirling is continuous whereas for the Rankine "on-off" modulation is typically used to control temperatures. This leads to an additional overall energy usage advantage for the Stirling. Efficiencies already measured are considerably higher than the original Rankine equipment. The total mass of the opposed Stirling pair is about 5kg.

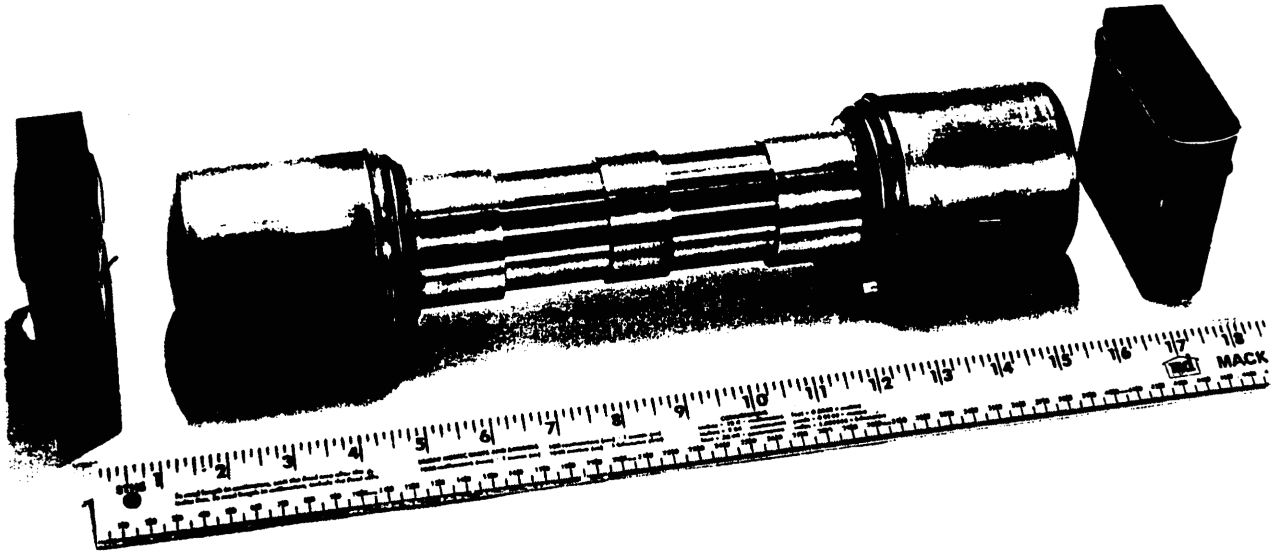


Figure 4 - General configuration of opposed free-piston Stirling cooler (cooling fans are at each end)

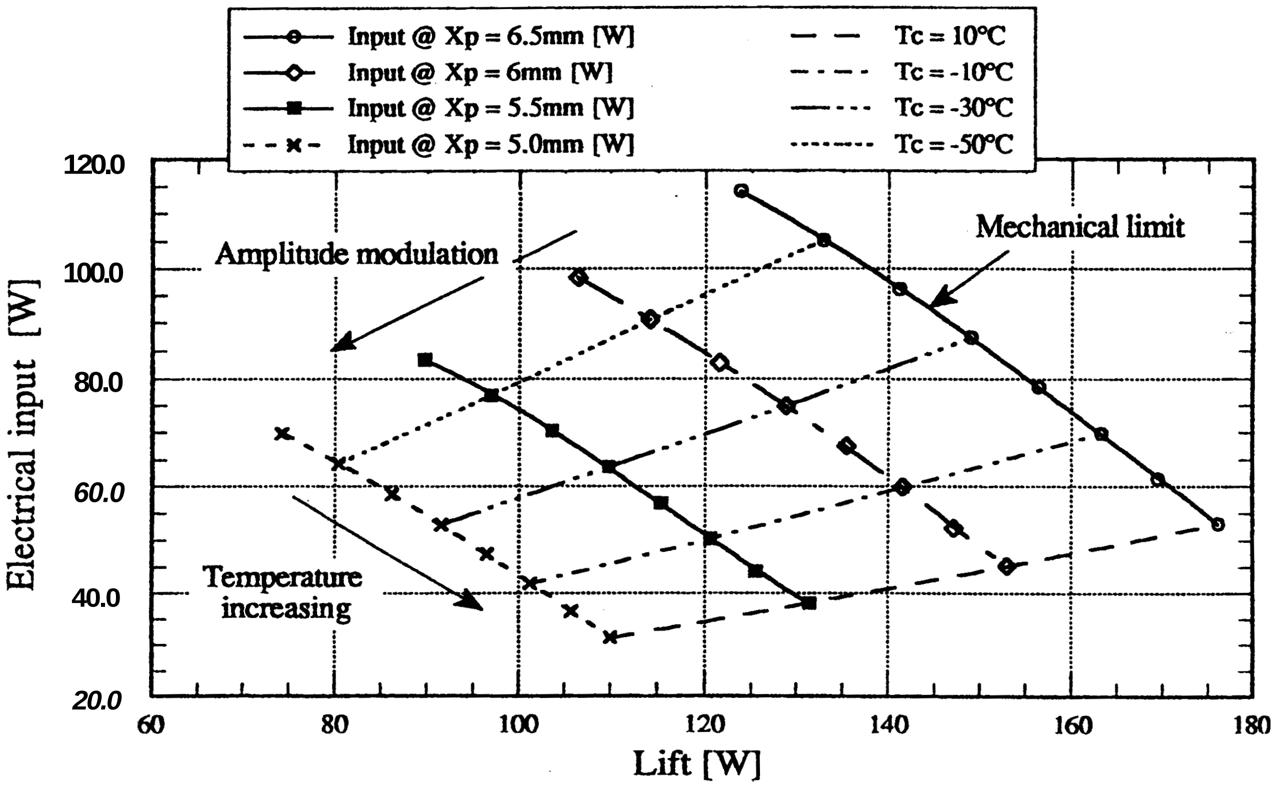


Figure 5 - Performance map for opposed free-piston Stirling cooler (input voltage controls the piston amplitude, X_p)

MINIATURE STIRLING COOLERS
by D.M.Berchowitz

PERFORMANCE AND SIZE LIMITS FOR FREE-PISTON STIRLING COOLERS

The machines shown in Figures 6 and 7 are representative of the current level of development of small free-piston Stirlings. Figure 6 shows a machine that lifts 35W at -50°C and Figure 7 shows a derivative cryocooler capable of lifting 4.0W at 77K. These machines are about 2.5kg mass and 86mm square at the fan end. The 35W machine is 205mm tall and the cryocooler is 260mm tall. Power input depends on a combination of lift and temperature. The motors are capable of absorbing 90W, however, the 35W cooler runs steady state at about 65W input. The cryocooler requires only 30W to maintain 77K but takes up to 90W at 4.0W lift. Both these machines operate at 60Hz which is considered to be high for mechanical devices of this type. To the first order, size is inversely proportional to frequency. So the higher the frequency the smaller the device. Free-piston Stirlings have the advantage over crank machines in that higher operational frequencies are possible since piston side loads are not a function of piston speed Crank machines are limited in this manner, particularly when lubrication is restricted Size is also affected by efficiency since lower inputs for a given lift lead to smaller motors and smaller heat rejectors.

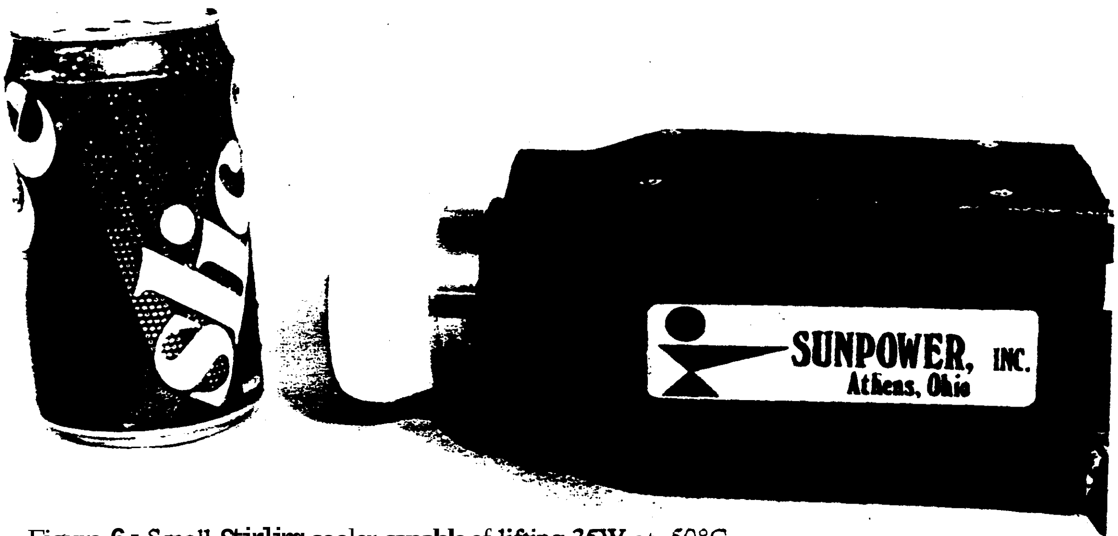


Figure 6 - Small Stirling cooler capable of lifting 35W at -50°C

Maximized performance for single stage machines lifting less than 100W and operating below -25°C (248K) is probably limited to around 60% of Carnot. At temperatures below about 100K the maximum fraction of Carnot tends to drop off from a likely figure of around 40%. Practical considerations associated with cost would reduce these numbers to some extent. Increasing frequency will also eventually have a deleterious effect on efficiency. At some point the reduction of size with increasing frequency is off set against the increase in size due to poorer efficiency. An exercise to design a miniature free-piston Stirling cooler for 80W lift at -50°C resulted in the hypothetical high frequency machine shown in Figure 8. Overall size is extremely small for a cooling machine of this capacity. The configuration and performance is similar to the 60Hz cooler shown in Figure 4 with the exception that the specific capacity has been increased from 16W/kg to 40W/kg.

MINIATURE STIRLING COOLERS
by D.M.Berchowitz

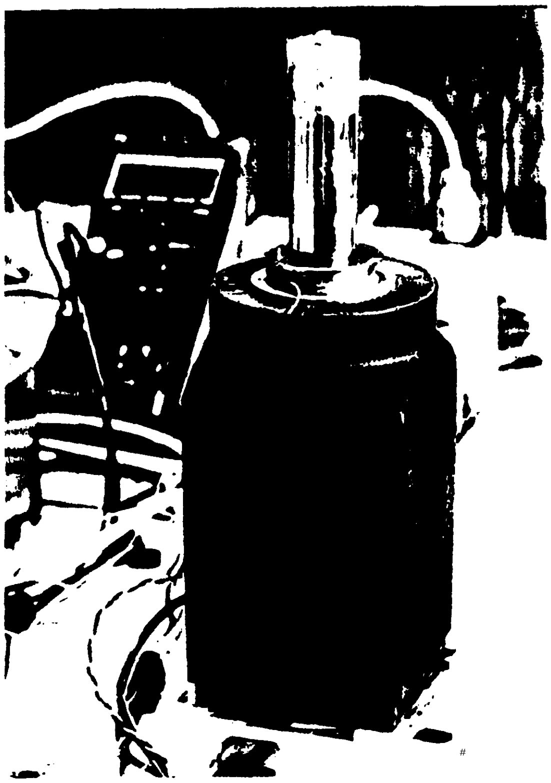


Figure 7 - Small cryocooler capable of lifting 4.0W at 77K (developed for high temperature superconductor applications)

SUMMARY

The free-piston Stirling offers the best choice for electronic cooling on the basis of reliability, size and performance. Cost estimates completed for larger machines would *suggest* that the Stirling may well be competitive in this area as well [5]. Exploratory applications *are* currently underway, a *good* example of which is the radar demonstrator shown in Figure 9. This unit, designed by Superconductor Technologies Inc. (STI), uses a small military-type Stirling (Hughes model 7050H-1SIA) to cool a high temperature superconductor delay line down to 80K. Though this exercise clearly demonstrates the merit of the Stirling cooler, military units *are* usually reliable for only a few thousand hours of operation. For an application of this nature, product life would need *to* be greatly improved while keeping cost below $2000 [7]. The machine shown in Figure 7 is designed to *meet* these needs. Lift has been increased by almost a factor of four while increasing the mass of the cooler by only 20%. Specific capacity improvement has been achieved partly by improving the cycle efficiency but mainly by the use of higher frequency. Though further improvements are still possible in this regard, low temperatures tend to limit the operational frequency for which the machine can be expected to operate efficiently.

MINIATURE STIRLING COOLERS
by D.M.Berchowitz

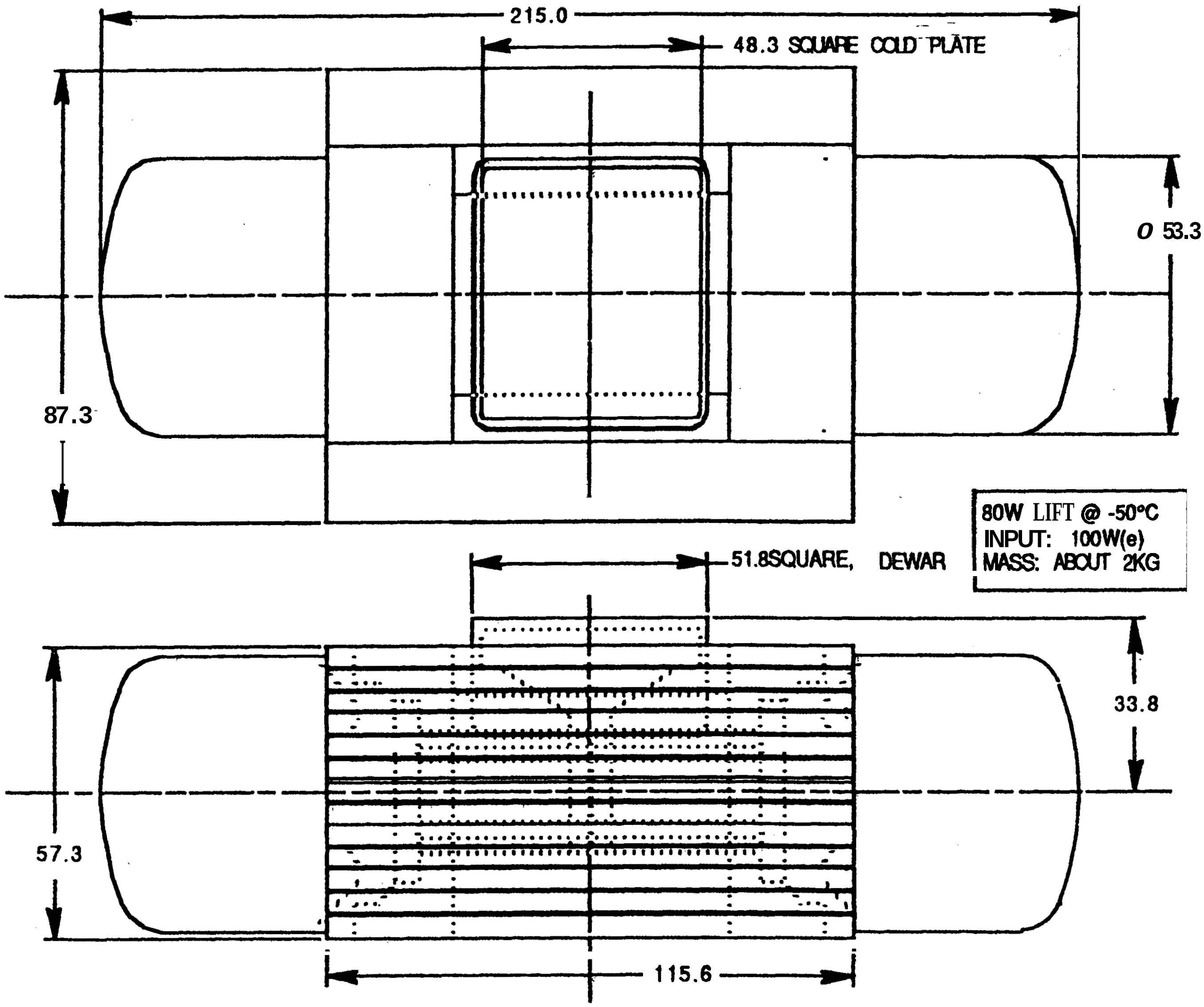


Figure 8 - Miniature free-piston Stirling cooler capable of lifting 80W at -50°C with 100W input (dimensions in mm).

The extent of miniaturization possibilities at warmer temperatures shows much more promise. Studies presently being undertaken suggest *that* for low lifts the operational frequencies may be greatly increased without sacrifice of thermodynamic performance. Mechanically, the ability of the free-piston configuration to operate reliably at far higher frequencies *than* crank machines is the other important ingredient. Some warm temperature comparisons *suggest* that the free-piston Stirling preserves performance far better than does the Rankine for small low lift applications. The eventual limitations dictated by heat flux demands will limit the process of size reduction. Where this boundary lies is still an unanswered question though some speculative ideas suggest that the Stirling may be miniaturized to the point of incorporating it directly into the silicon structure of a microprocessor [8].

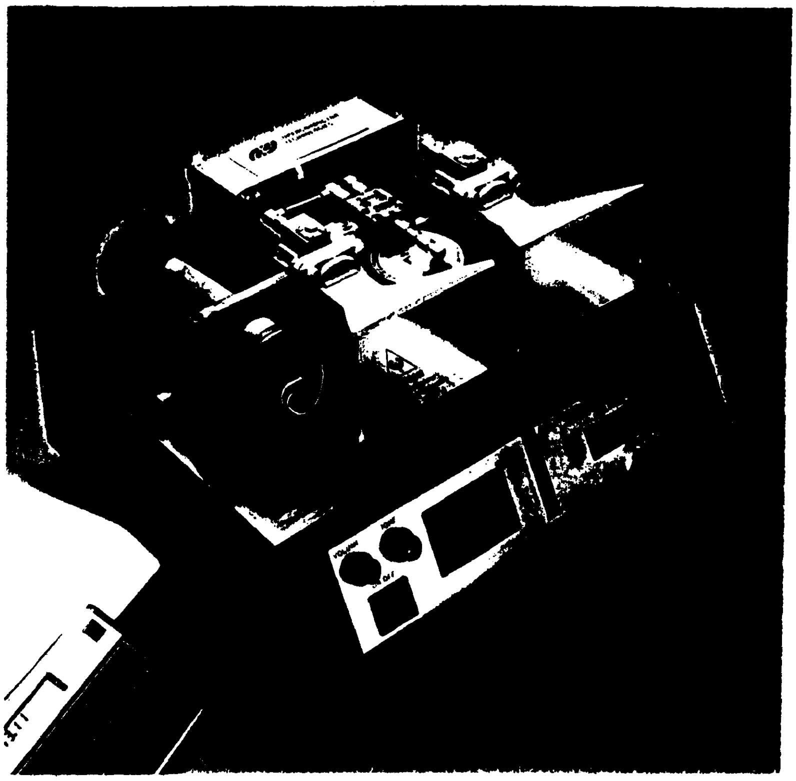


Figure 9 - Radar demonstrator using high temperature superconductor delay line cooled by small Stirling (courtesy STI)

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8. Walker G. and Bingham E.R. "Micro and Nano Cryocoolers: Speculation on Future Development", 6th Int. Cryocooler Conf. Plymouth, Mass., Oct 1990, pp 363-375.

NASA Paper on Stirling Cryocooler
In-X uses a similar model

Stirling Refrigerator for Space Shuttle Experiments

Kelly McDonald
Martin Marietta Services, Inc.
David Berchowitz, Ph.D.
Sunpower, Inc.
John Rosenfeld, P.E.
James Lindemuth Thermacore, Inc.

Presented at the 29th lntersociety Energy Conversion Engineering Conference, Monterey, CA
August 7-11, 1994.

Abstract

In October 1992 Martin Marietta Services was tasked by NASA's Life Sciences Projects Division at the Johnson Space Center to design and develop an Orbiter Refrigerator/Freezer (OR/F) based on a Stirling cycle cooler. OR/F's are used in the Shuttle mid-deck to store experiment samples, primarily blood and urine.

The Stirling Orbiter Ref/Frzr (SOR/F) uses a horizontally opposed Stirling cooler designed by Sunpower, Inc. of Athens, OH. The cooler is lightweight and efficient, and uses helium as the working fluid instead of a CFC. A pair of acetone heat pipes is used to transfer heat from the cold volume to the cooler where it is rejected to cabin air. The heat pipes do not require a pump or electronics, which helps to keep the overall system simple and efficient. The heat pipes were developed by DTX/Thermacore, Inc. of Lancaster, PA. The SOR/F also utilizes a new insulation, precipitated silica. The improved insulation allows for a reduction in cooler size.

The SOR/F has a total lift of greater than 85W (net lift 55W) at -22°C and uses 70W input power. Besides meeting its thermal specifications the SOR/F meets another primary design goal: it reduces acoustic noise. The unit has operated for over 600 hours and was flown successfully aboard STS-60, SpaceHab 2 in February 1994.

Introduction

Refrigerator/Freezers are currently used on board the Space Shuttle to support science experiments. Life Sciences missions depend heavily on the ref/frzr's for the preservation of urine, blood and saliva samples. The SOR/F project was initiated to develop a replacement to the existing OR/F's. The unit is the size of two mid-deck lockers, weighs 45.8 kg (101 lbs.) and is supplied with 28 VDC. It must maintain a cooled volume of 0.3 m^3 (1.2 ft^3) between 10" and -22°C and provide 50 W of net lift. An emphasis was also placed on meeting the Orbiter payload acoustic specifications. While operation during ascent is not required, it was decided that the Stirling cooler would remain operational during this period in order to simplify the design. The SOR/F consists of three major subsystems: the Stirling cooler, a pair of acetone heat pipes and the cold volume. Detailed requirements are available in the Specification and Assembly Drawing (LS-30106).

Stirling Cooler

The Stirling cycle alternately compresses a fixed mass of gas (usually helium) at one temperature level and expands it at another in a closed regenerative cycle in order to either lift heat or do work. The thermodynamic cycle is covered in more detail elsewhere (1, 2, 3, 4). Suffice it to say that in its ideal form, the Stirling cycle has the highest possible efficiency of any thermodynamic cycle. The particular configuration used here (Figure 1) is an opposed fiee-piston machine which offers advantages in reliability, quietness of operation and simple capacity modulation. This machine is a modification of the Sunpower Minicooler originally developed for cooling electronics (5).

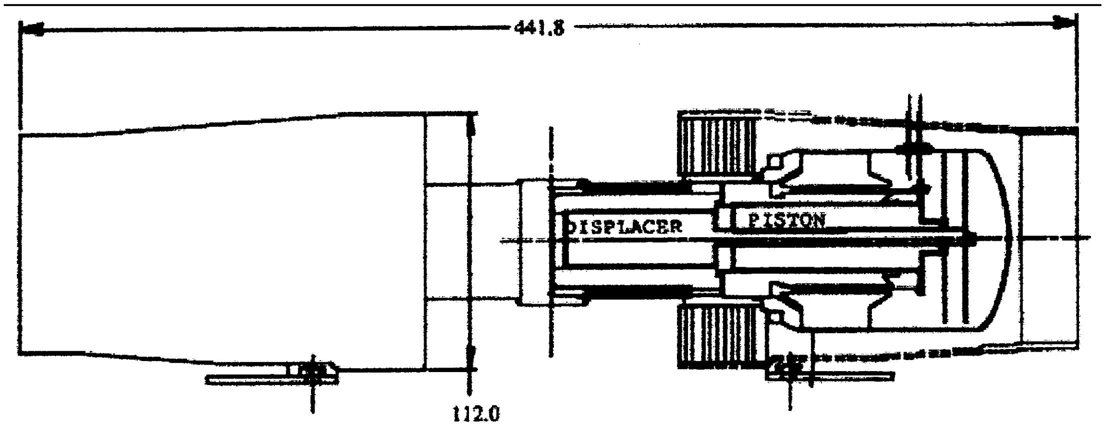

Figure 1 Opposed Free-Piston Stirling Cooler (Dimensions in mm)

Basic Design Requirements

a) **124W of lift** at **4°C box** temperature **and** 88W at -22°C **box** temperature. Ambient in both cases is **23°C.** A temperature difference of 12°C was assumed between the **box** temperature and the Stirling cold end.
b) Maximum temperature of the air at the rejector exits is not to exceed **49°C.**
c) Maximum inaccessible **surface** temperatures are to be below 49°C **during** normal operation.
d) **Must** operate **m** ambient conditions **from 5°C** to **35°C.**
e) Voltage supply is 28 VDC ±**4 VDC.** Consumption **may** not exceed **300W** intermittent and **200W** continuous.

Description

Two modified Minicoolers were arranged in an opposed configuration. By operating the machines 180" out of phase, all else being equal, the residual casing vibrations are nulled. In practice, the machines do not operate in identical modes. There is always some discrepancy in amplitudes and phases between the moving parts. These discrepancies result in a residual casing vibration. Therefore, in order to obtain the lowest vibration levels, circuitry was provided to alter the input to one linear motor with respect to the other. By adjusting the relative voltage and phase between the two drive voltages, it is possible to achieve extremely low vibration levels. This adjustment was made manually as part of the final tuning of the system. For the application at hand, an active vibration control system was seen as unnecessarily elaborate since the only purpose of minimizing vibration was to control noise. An additional advantage of the opposed configuration is that, for the same levels of residual vibration, it has a much better specific capacity (Lift/Mass) than a single sided machine owing to the absence of the balance mass.

Additional modifications included improving the reliability of the motors and reoptimizing the heat exchangers for higher efficiencies at warmer temperatures. About forty units of the Minicooler have been fabricated and extensive operating experience has been obtained. This has made it possible to calibrate the design calculations to a high level of confidence.

The electronic package consists of the driver section which is responsible for supplying the motors with pulse width modulated square waves. Modulation of the cycle is achieved by controlling the piston amplitudes which is proportional to the RMS drive voltages. The control circuit determines an error signal between a user set temperature and a measured temperature and adjusts the drive voltages to minimize the error. The system therefore responds to

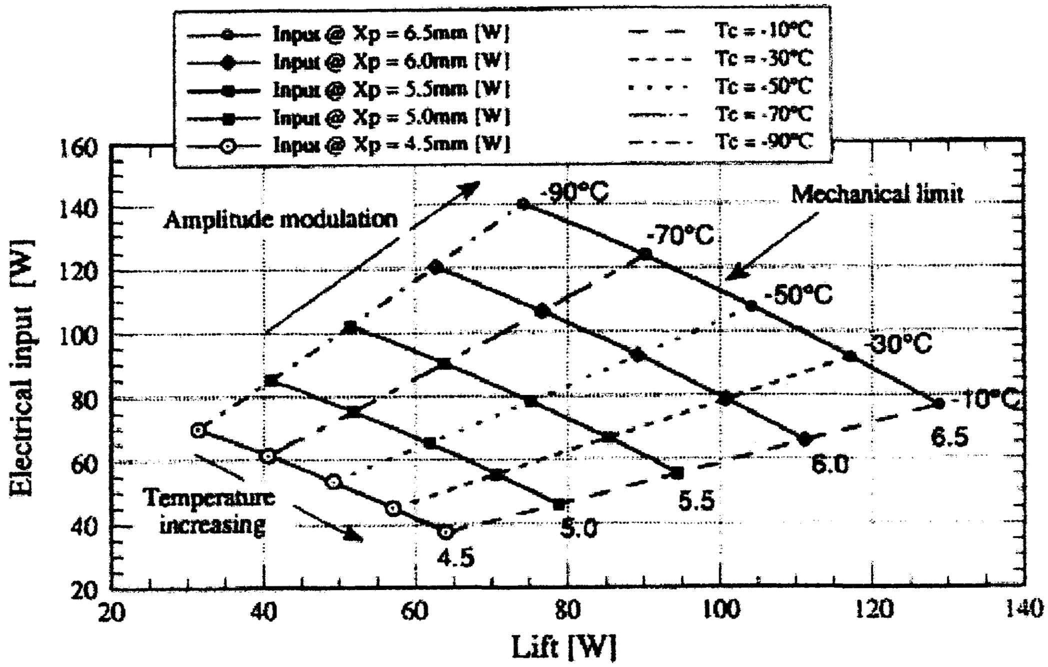

Figure 2 Calibrated Calculation of Performance Map (Reject Temperature Fixed at 45°C)

temperature variations in the cold space by adjusting the amplitudes of the pistons. If the temperature in the cold space is constant, then the cooler adjusts its lift to just balance the heat leak. This temperature control system minimizes cycle losses and therefore input. If the motor temperatures exceed a set value, then the temperature control is overridden and the drive is essentially switched off. Signal points for motor currents and various temperatures are provided for observation and data down-link.

Analysis

The analysis of the cooler follows that outlined in [4]. In its simplest form, the cooler may be described as a tuned mechanical oscillator where the resonances of the displacer and piston are designed so as to obtain optimum phase angles for both thermodynamic and electrical performance. The flow conditions within the cooler are somewhat chaotic and precise analysis is intractable even though the response of the system is remarkably linear [6]. Generally, a combination of approaches including oscillatory flow models, non-steady heat transfer and empiricism has proved to be successful in predicting the performance of these machines. Figure 2 shows the calculated performance *map* which includes the losses associated with the linear motors. The cold-side and warm-side temperatures are assumed to be measured on the outside walls of the acceptor and rejector respectively. In practice, the warm side temperature is proportional to the rejected heat and therefore varies with load and setpoint temperature. For the purposes of this graph, the warm-side is assumed fixed at 45°C, which is typical of the reject temperature at the higher capacities. Especially interesting from Figure 2 is the cooler's ability to maintain a reasonable capacity and efficiency over a wide range of operating temperatures.

Figure 3 shows the linear motor performance as calculated. Bench tests which determine the total AC resistance and the motor constant (Volt-seconds) verify that the performance follows the predicted map. Discrepancies at the lower powers are more likely owing to the difficulty of determining the effects of structure on fringe losses,

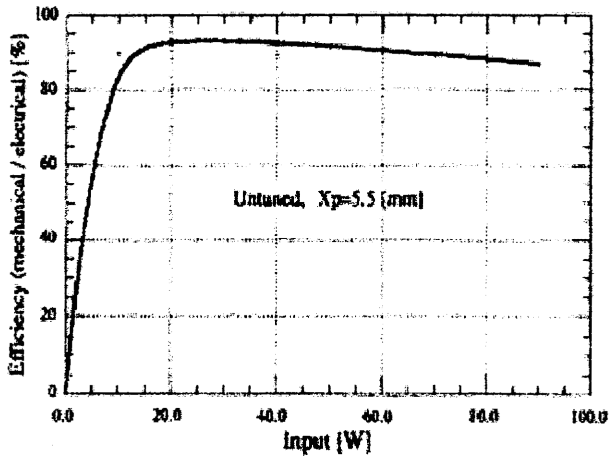

Figure 3 Linear Motor Calculated Efficiency at Design Amplitude (input per side)

Bench testing

Figure 4 shows actual performance as measured on the bench. These data were taken from the third unit built in a batch of three. Inputs appear to be some 10 W higher than anticipated. From subsequent work, it is now known that part of this is due to center-port and gas bearing losses.